

Lesquerella seed production: Water requirement and management

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Abstract

Lesquerella synthesizes unique hydroxy fatty acids (HFA) with potential industrial and consumer applications. However, information about its water use requirement and yield response to irrigation is limited. Detailed irrigation studies were conducted with *Lesquerella fendleri* (Gray) Wats. on a sandy loam in Arizona during the 1991–1992 and 1992–1993, fall–spring seasons to determine its water requirement and yield. In 1991–1992, dry matter yield was linearly related to the total evapotranspiration (ET). The highest dry matter yield was obtained for a control irrigation treatment with seven post-emergence irrigations. Four limited water treatments were given either three or four irrigations, and yielded 26–36% less dry matter than the control. Total ET for the control was 634 mm, whereas ET for the limited water treatments varied from 460 to 500 mm. Total seed yield in 1991–1992, was not determined. However, seed oil content was significantly higher for the control than for the limited water treatments. In 1992–1993, *Lesquerella* was grown under eight irrigation treatments: weekly (W; 12 post-emergence irrigations), biweekly (B; 7), weekly with two supplemental irrigations in early winter (WS; 14), biweekly with two supplemental irrigations in early winter (BS; 9), and four treatments that were irrigated like treatment B, except that irrigation was withheld during early flowering (B1; 5), withheld during mid-flowering (B2; 6), withheld at full bloom (B3; 6), and withheld during seed formation and ripening (B4; 5). Irrigation treatments affected both the dry matter and seed yield, but not the seed oil content and lesquerolic acid content of the oil. Withholding irrigation on the biweekly application during mid-flower and during seed formation and ripening resulted in the lowest seed yields. The BS treatment had the highest dry matter (7020 kg/ha) and seed yield (888 kg/ha), suggesting a possible yield benefit from the early winter irrigations. Total ET for treatments varied from 535 to 767 mm, and both dry matter and seed yield were related to total ET (although not by linear relationships). Total ET corresponding to the maximum yield was 668 mm. A water management that allows $\approx 50\%$ depletion of the available soil water from the onset of flowering through seed ripening can result in maximum growth and yield. Providing irrigation every 14 days during this period may be optimum for *Lesquerella* grown on sandy loam soils. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: *Lesquerella fendleri*; Seed yield; Oil content; Evapotranspiration; Irrigation

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1. Introduction

Seed oils of *Lesquerella* species (*Brassicaceae*) have unique hydroxy fatty acids (HFA) with potential industrial and consumer applications in the production of resins, waxes, cosmetics, nylons, plastics, coatings and lubricating greases (Kleiman, 1990; Roetheli et al., 1991; Dierig et al., 1993). The chemical structure of one of these HFA, lesquerolic acid, also provides additional opportunities for developing new products (Thompson and Dierig, 1994).

Lesquerella fendleri (Gray) Wats. is native to the semi-arid southwestern United States and has the best potential for domestication and commercialization (Thompson et al., 1989). Progress has been made towards developing *L. fendleri* as a fall-planted, winter annual crop. Agronomic studies in central Arizona have provided information on planting date (Dierig et al., 1993; Nelson et al., 1996), seed-bed preparation and seeding rate (Dierig et al., 1993), plant population (Thompson et al., 1989), fertilization (Nelson et al., 1996), harvesting methods (Coates, 1994) and harvesting date (Brahim et al., 1996; Coates, 1996).

Water use requirement and irrigation management information for *Lesquerella* is limited. Roetheli et al. (1991) and Dierig et al. (1993) reported that fall-planted *Lesquerella* in central Arizona uses ~600–625 mm of water. Most of the water is needed during the crop's flowering and reproductive period that starts in late February and continues through May. Because precipitation in central Arizona is low during February through May, irrigation is required for high yields (Roetheli et al., 1991). However, the seasonal evapotranspiration rates for *Lesquerella* have not been quantified, making water management decisions imprecise. While the timing of irrigation applications has an apparent effect on the yield of *Lesquerella* (Dierig et al., 1993), information about the yield response to limited water at particular times during the growing season is unavailable. During the cropping years of 1991–1992 and 1992–1993, we conducted irrigation studies on *L. fendleri* in central Arizona to determine its water use requirement and yield response under differential irrigation. This information is needed

to identify efficient water management strategies that can be used by commercial growers of this new industrial crop.

2. Materials and methods

2.1. Experimental site and irrigation treatments

Extensive irrigation studies were conducted with *L. fendleri* (Gray) Wats. in the 1991–1992, and 1992–1993, fall–spring growing seasons on two, adjacent, 0.4 ha sites at The University of Arizona, Maricopa Agricultural Center, ~20 km south of Phoenix, Arizona. The soil is a Mohall sandy loam (fine-loamy, mixed hyperthermic, Typic Haplargid) and has a water holding capacity of ~120 mm/m (Post et al., 1988). Field preparations prior to each planting included disking, land leveling and incorporating ammonium phosphate fertilizer at a rate of 56 kg N ha⁻¹ and 70 kg P ha⁻¹. Following these operations, the sites were furrowed, forming raised beds spaced 1 m apart. *L. fendleri* was planted at a seeding rate of 9 kg ha⁻¹ with a spreader-cultipacker type planter on 11 October, 1991 and on 1 October 1992, for the 1991–1992 and 1992–1993 studies, respectively. Immediately following each planting, 200 mm of water was applied to provide adequate soil moisture for germination and seedling establishment.

After plant emergence, 20 experimental plots (8 m wide by 25 m long) were formed in early November 1991, and 40 experimental plots (8 m wide by 12.5 m long) in late October 1992. Each plot had seven raised beds. The experimental design for both years was a randomized complete block, which consisted of five irrigation treatments with four replications for 1991–1992, and eight irrigation treatments with five replications for 1992–1993. For both growing seasons, surface irrigation was applied to individual plots using a gated pipe irrigation system. Because the plots were bordered on all ends, there was no runoff. Irrigation water applications were measured with a calibrated, in-line propeller-type water meter that had a rate indicator and volume totalizer. Water amounts applied to plots were determined

Table 1

Post-emergence irrigation dates and amounts (mm) for irrigation treatments in 1991–1992, and 1992–1993

Irrigation dates 1991–1992	Control	Irrigation treatments 1991–1992						
		L1	L2	L3	L4			
Feb 26	65	65	65	65	65			
Mar 18	65	65	NI †	65	65			
Apr 8	65	65	65	NI	65			
Apr 15	60	NI	NI	NI	NI			
Apr 23	65	65	65	65	NI			
Apr 29	60	NI	NI	NI	NI			
May 7	60	NI	NI	NI	NI			
Total	440	260	195	195	195			
Irrigation dates 1992–1993	Irrigation treatments 1992-1993							
	WS	W	BS	B	B1	B2	B3	B4
Dec 3	35	NI	35	NI	NI	NI	NI	NI
Feb 4	35	NI	35	NI	NI	NI	NI	NI
Feb 19	20	20	30	35	NI	35	35	35
Feb 24	20	20	NI	NI	NI	NI	NI	NI
Mar 2	35	35	50	50	NI	50	50	50
Mar 12	40	40	60	60	60	60	60	60
Mar 17	40	40	NI	NI	NI	NI	NI	NI
Mar 26	50	50	80	80	80	NI	80	80
Apr 2	50	50	NI	NI	NI	NI	NI	NI
Apr 12	50	50	60	60	60	60	NI	60
Apr 17	50	50	NI	NI	NI	NI	NI	NI
Apr 24	50	50	60	60	60	60	60	NI
Apr 30	50	50	NI	NI	NI	NI	NI	NI
May 5	50	50	60	60	60	60	60	NI
Total	575	505	470	405	320	325	345	285

† No irrigation.

from the change in meter volume over time, divided by the plot area.

In the first study (1991–1992), irrigation treatments included a well-watered, control treatment (treatment C) and four, limited water treatments (Table 1). The control treatment received a total of 440 mm of post-emergence irrigation in 1992, applied with seven irrigations (each with 60–65 mm of water) that included one irrigation on 26 February at initial flowering (IF), one on 18 March at about mid-flower (MF), another on 8 April at full bloom (FB), and then four irrigations made at weekly intervals through 7 May. Treatment L1 received a total of 260 mm from four, post-emergence irrigations, where one 65 mm irrigation was applied at IF, MF, FB, and on 23 April at seed formation (SF). Treatments L2, L3

and L4 all received a total of 195 mm from three, 65 mm irrigations. Irrigation was withheld at MF for L2, at FB for L3 and at SF for L4. Unlike treatment C, the final irrigation was on 23 April for treatments L1, L2 and L3 and on 8 April for L4.

In 1992–1993, the eight irrigation treatments (Table 1) included weekly (W) and biweekly (B) irrigations that were started on 19 February 1993, at initial flowering, and were ended on 5 May 1993; weekly (WS) and biweekly (BS) irrigation treatments that also received one supplemental irrigation during early vegetative growth on 3 December 1992, and another prior to flowering on 4 February 1993; and four treatments, designated as B1, B2, B3 and B4, that were irrigated like treatment B, except that one or two regular bi-

weekly irrigations were withheld at certain times during the growing season. Biweekly irrigation was not started until 12 March at MF for B1; was withheld between 13 March through 11 April (MF through FB) for B2; was withheld between 27 March through 23 April (FB through SF) for B3, and was withheld after 12 April (FB through seed ripening) for B4. Unlike the 1991–1992 study, where 60–65 mm of water was applied per irrigation for all treatments, irrigation amounts in 1992–1993 were generally slightly higher for biweekly than weekly treatments to account for the longer irrigation cycles of the biweekly treatments; and irrigation amounts for treatments were increased as the atmospheric evaporative demand increased during the season. Total amounts of post-emergence irrigation for treatments in the 1992–1993 season ranged from 285 to 575 mm of water (Table 1).

2.2. Soil water content measurements and crop evapotranspiration

Neutron access tubes, 2.0 m in length, were installed in the center bed of each plot in early December 1991 and in early November 1992. A neutron probe, calibrated at the sites, was used to measure the volumetric soil water contents for the plots in 0.2 m increments to a depth of 2.0 m. In 1991–1992, soil water content was measured for all treatments for the first time on 4 December 1991, and for the last time on 27 May 1992. The water contents were measured on 30 days for the C treatment and on 27 days for the L1, L2, L3 and L4 treatments. In 1992–1993, water content was measured for all treatments for the first and last times on 3 November 1992 and 27 May 1993, respectively. They were measured on 34 days for the W and WS treatments and on 27 days for all other treatments in 1992–1993. In both experiments, treatment water contents were measured several times during early seedling growth, every 7–14 days during January, and before and after most treatment irrigations during February through May.

Lesquerella crop evapotranspiration (ET) was calculated for all treatments from 4 December 1991 to 26 May 1992, in 1991–1992, and from 3

November 1992 to 26 May 1993, in 1992–1993, by the soil water balance (Jensen, et al., 1990),

$$ET = I + R - D + \Delta S \quad (1)$$

where: ET, crop evapotranspiration (mm); *I*, irrigation (mm); *R*, rainfall (mm); *D*, deep drainage (mm); ΔS , change in soil water storage (mm).

Daily climatic data, including rainfall amounts, were obtained with the Arizona Meteorological Network weather station (Brown, 1987), situated over a uniform grass and located 100 m from the field site. The change in soil water storage was calculated over a 2.1 m soil profile. Since deep drainage was not measured, the calculations for ET included any water movement that may have occurred below the 2.1 m soil profile. Daily ET, computed for periods of 5–19 days during the two *Lesquerella* seasons, was compared to climatic estimates of reference crop (grass) evapotranspiration (ET_o) calculated with the Doorenbos and Pruitt (1977) adaptation of the Penman equation. The ratio of ET to ET_o is defined as the crop coefficient (Jensen et al., 1990).

The winter months in both experiments were exceptionally cool, cloudy and wet for central Arizona. Warm and dry conditions prevailed starting in early April for 1991–1992, and in late March for 1992–1993. In 1991–1992, heavy rainfall occurred in all months, except January and April, and the total rainfall (November–May) was 207 mm. In 1992–1993, total rainfall (November–May) was 171 mm, but the majority of the total occurred from late November through mid-January, whereas no measurable rainfall occurred during April and May.

2.3. Yield measurements

In both studies, yield sites (2.0 m²) were established in all plots in early February. Plants were hand-harvested on 16 June 1992, and on 6 June 1993. Plants within the sample areas were counted, clipped at the soil line and air-dried. Total aboveground plant dry weights were determined before hand-threshing the seed. The seed was then cleaned and weighed. No seed yields are reported for the 1991–1992 treatments because a

heavy rain and hailstorm prior to harvest on 28 May 1992, resulted in severe seed shattering and, consequently, the loss of a high percentage of the seed yield. In both years, the 1000-seed weight, the seed oil content and the lesquerolic acid content of the oil were evaluated. Seed oil content and lesquerolic acid composition were determined at the National Center for Agricultural Utilization Research, Peoria, IL (B.S. Phillips, personal communication, 1992; 1993) for both studies. The effects of irrigation treatments on plant dry matter yield, seed yield, seed weight and seed oil characteristics were statistically analyzed using the General Linear Models (GLM) Procedure (SAS Institute, 1988). When a significant analysis of variance (ANOVA) occurred, Duncan's multiple range test (Steele and Torrie, 1980) was used to separate treatment means.

3. Results

3.1. Soil water content

The average measured soil water contents within the 0–2.1 m soil profile from 4 December (Day of Year 338 (DOY 338)) 1991, through 27 May (DOY 148) 1992, are shown for treatments in 1991–1992, in Fig. 1. The soil water content at field capacity and wilting point for the 0–2.1 m soil layer is ~ 525 and 275 mm, respectively, and 50% available soil water occurs at ≈ 400 mm. Winter and early spring rains, and post-emergence irrigation that began for treatments on 26 February (DOY 57), 1992, were sufficient to maintain $> 50\%$ available soil water for all treatments through at least mid-April, when the crop was in full bloom. Treatment C with weekly irrigations started in April had higher soil water than those for the limited water treatments from mid-April through the end of May. After the last irrigation for treatments L1, L2 and L3 on 23 April (DOY 114), the soil water content for those treatments decreased to $< 50\%$ available on ~ 6 May (DOY 127), whereas the soil water content for treatment L4 decreased to $< 50\%$ available on 25 April (DOY 116) following the last irrigation for that treatment on 8 April (DOY 99).

For 1992–1993, the average soil water contents (over the 0–2.1 m soil profile) from 3 November (DOY 308) 1992, through 27 May (DOY 147) 1993, are shown for treatments W, WS, B and BS in Fig. 2a, and for treatments B1, B2, B3 and B4 in Fig. 2b. Supplemental irrigation with 35 mm of water was provided to the WS and BS treatments on 3 December (DOY 338) 1992, and on 4 February (DOY 35) 1993, and the profile soil water content for those treatments was higher than for other treatments during early winter months. However, frequent rainfall during late December and early January added 90 mm of water to the soil profile for all treatments, such that each treatment had at least 465 mm of soil water storage on 19 January (DOY 19) 1993. From 19 January through 14 May (DOY 134), the soil water content for treatments W, WS, B, BS (Fig. 2a) and B1 (Fig. 2b) was maintained $> 50\%$ available, and was highest for the WS treatment profile during that period. The soil water for treatments B2, B3 and B4 (Fig. 2b) decreased to $< 50\%$ available, starting shortly after a treatment's irrigation was withheld, i.e. beginning in early April at full bloom for B2, in mid-April after full bloom for B3, and in late April at seed formation for B4. Because irrigation was resumed for B2 in mid-April and for B3 in late April, those treatments had higher soil water during the latter stages of the season than that for B4, whose last irrigation was on 12 April (DOY 102).

3.2. Evapotranspiration

The soil water balance from 4 December 1991 to 26 May 1992, is shown for all treatments in 1991–1992 in Table 2. As expected, treatment C had the highest total ET. The 634 mm of total ET for the control treatment was similar to the seasonal water use estimates made for *Lesquerella* in previous studies at this location (Roetheli et al., 1991; Dierig et al., 1993). The crop coefficient (ratio of daily ET to daily E_{To}) for treatment C gradually increased from 0.20 during early December 1991, and reached a value of 1.01 about mid-March 1992. From late-March through early May, treatment C used water at a rate of 0.94–1.14 times the reference crop evapotranspiration.

Table 2
Evapotranspiration for all irrigation treatments in 1991–1992

Calendar dates 1991–1992	Days in period	Rainfall (mm)	Control			L1			L2			L3			L4		
			Irrigation (mm)	ET rate (mm/day)	ET/ ETo †	Irrigation (mm)	ET rate (mm/day)	ET/ETo	Irrigation (mm)	ET rate (mm/day)	ET/ETo	Irrigation (mm)	ET rate (mm/day)	ET/ETo	Irrigation (mm)	ET rate (mm/day)	ET/ETo
December 4–Dec 8	15	20		0.39	0.20		0.37	0.19		0.43	0.22		0.33	0.17		0.47	0.24
Dec 19–Dec 28	10	14		0.70	0.39		0.82	0.45		0.71	0.39		0.73	0.40		0.69	0.38
Dec 29–Jan 8	11	7		0.93	0.54		0.90	0.53		0.84	0.49		0.77	0.45		0.87	0.51
Jan 9–Jan 21	13	6		1.07	0.38		0.97	0.35		1.28	0.46		1.35	0.48		0.33	0.48
Jan 22–Feb 4	14	2		1.44	0.46		1.41	0.45		1.33	0.43		1.48	0.47		1.23	0.39
Feb 5–Feb 11	7	26		1.37	0.68		1.56	0.78		1.66	0.83		1.36	0.68		1.53	0.76
Feb 12–Feb 19	8	12		2.01	0.69		1.71	0.58		2.03	0.69		1.81	0.62		2.11	0.72
Feb 20–Mar 4	14	12	65	2.94	0.76	65	2.71	0.70	65	3.03	0.78	65	2.84	0.74	65	2.79	0.72
Mar 5–Mar 17	13	12		3.52	0.84		3.50	0.84		3.58	0.85		3.73	0.89		3.67	0.88
Mar 18–Mar 24	7		65	5.31	1.01	65	4.90	0.93		3.26	0.62	65	5.60	1.06	65	5.87	1.11
Mar 25–Apr 7	14	49		5.16	1.09		5.22	1.10		3.83	0.81		4.94	1.04		5.16	1.09
Apr 8–Apr 14	7		65	6.53	0.94	65	5.47	0.82	65	4.61	0.66		3.57	0.51	65	5.49	0.79
Apr 15–Apr 21	7		60	8.84	1.14		6.50	0.84		5.26	0.68		4.63	0.60		6.19	0.80
Apr 22–Apr 27	6		65	9.15	1.12		6.23	0.76	65	6.12	0.75	65	4.92	0.60		4.72	0.58
Apr 28–May 5	8	11		8.40	0.99		5.50	0.65		5.15	0.61		5.20	0.62		4.36	0.52
May 6–May 11	6		60	8.40	1.08		4.13	0.53		4.53	0.58		3.82	0.49		2.80	0.36
May 12–May 19	8	3		6.83	0.78		3.43	0.39		3.76	0.43		2.78	0.32		1.98	0.23
May 20–May 26	7			2.81	0.40		1.24	0.18		1.37	0.20		1.07	0.15		0.89	0.13
Total rainfall (mm)		174															
Total irrigation (mm)			440			260			195			195			195		
Total ET (mm)				634			500			465			460			469	

† ETo is the grass-reference evapotranspiration calculated by the modified Penman equation (Doorenbos and Pruitt, 1977).

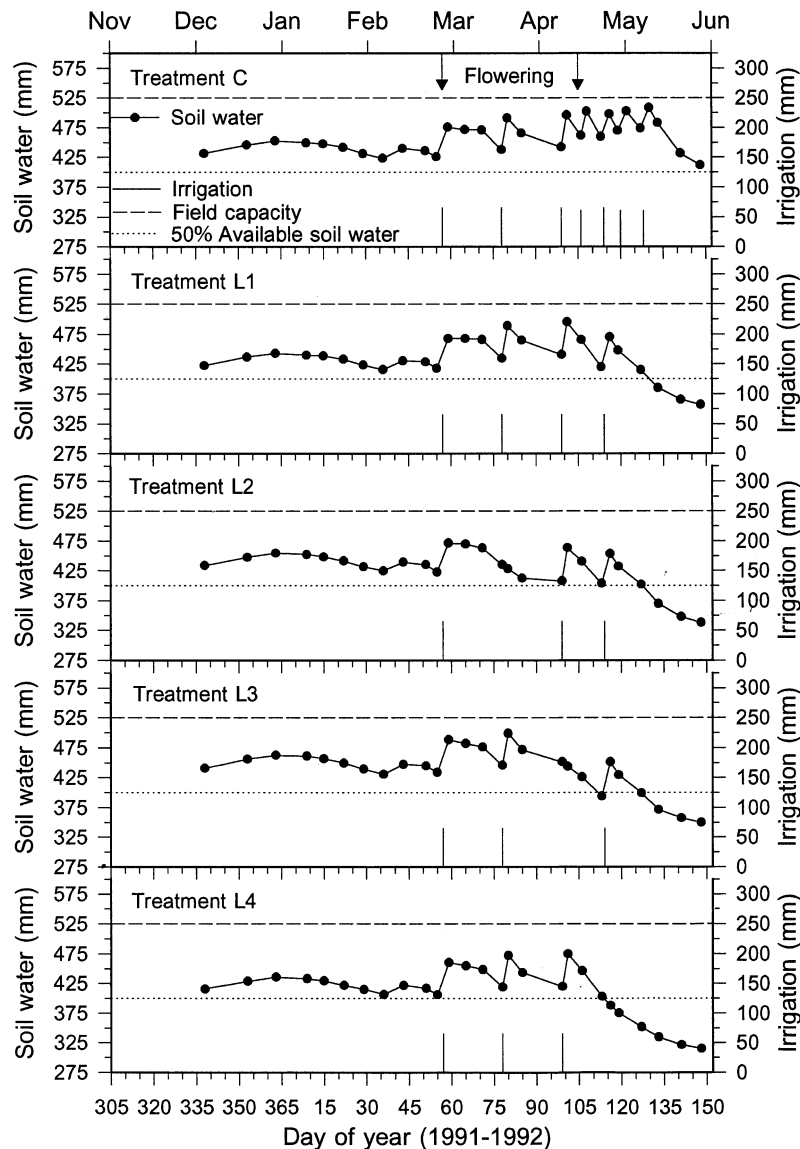


Fig. 1. Average measured soil water (0–2.1 m) for all irrigation treatments in 1991–1992 season.

The peak ET rate for treatment C was 9.15 mm/day and occurred during the period 22–27 April. The total ET for the four limited water treatments in 1991–1992 was reduced from 21 to 27% below that for treatment C and ranged from 460 to 500 mm. Evapotranspiration rates were similar for all treatments from December 1991 through early March 1992. On 18 March, irrigation was given to all treatments except L2, which resulted in a

lower ET than the other treatments during the second-half of March. Irrigation was given to all treatments except L3 on 8 April, and its ET was depressed during mid-April. Treatment L4 was not irrigated after 8 April, and its ET was the lowest from late April through the remainder of the season. From mid-April through mid-May, daily ET for the control was on the order of 2–4 mm/day higher than the other limited water treat-

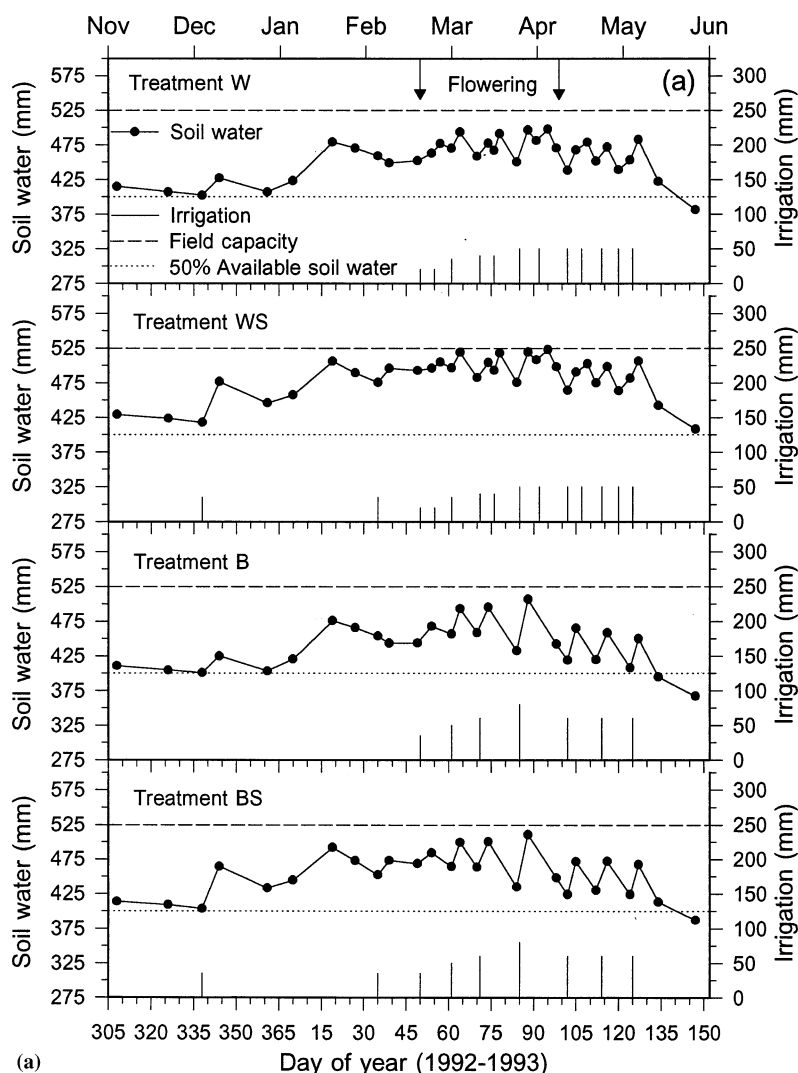


Fig. 2. (a) Average measured soil water (0–2.1 m) for irrigation treatments W, WS, B and BS in 1992–1993. (b) Average measured soil water (0–2.1 m) for irrigation treatments B1, B2, B3 and B4 in 1992–1993.

ments, whose irrigation was terminated in late April.

Cumulative crop ET with time for treatments in 1991–1992 (Fig. 3), shows that > 510 mm, or 80%, of the 634 mm of total ET for the control occurred after 1 March (DOY 61) 1992. From 15 April (DOY 106) through late May, the control used from 120 to 165 mm more water in ET than the limited water treatments.

The soil water balance from 3 November 1992 to 26 May 1993, is shown for treatments WS, W,

BS and B in Table 3a, and for treatments B1, B2, B3 and B4 in Table 3b, for the 1992–1993 study. In 1992–1993, the highest total ET was 767 mm for treatment WS, whereas the lowest total ET was 535 mm for treatment B4. The supplemental irrigations given to the WS and BS treatments in early December 1992, and early February 1993, resulted in higher ET rates during December through early March than for treatments without supplemental irrigation. The ET:ET₀ ratio (crop coefficient) for the WS and BS treatments in-

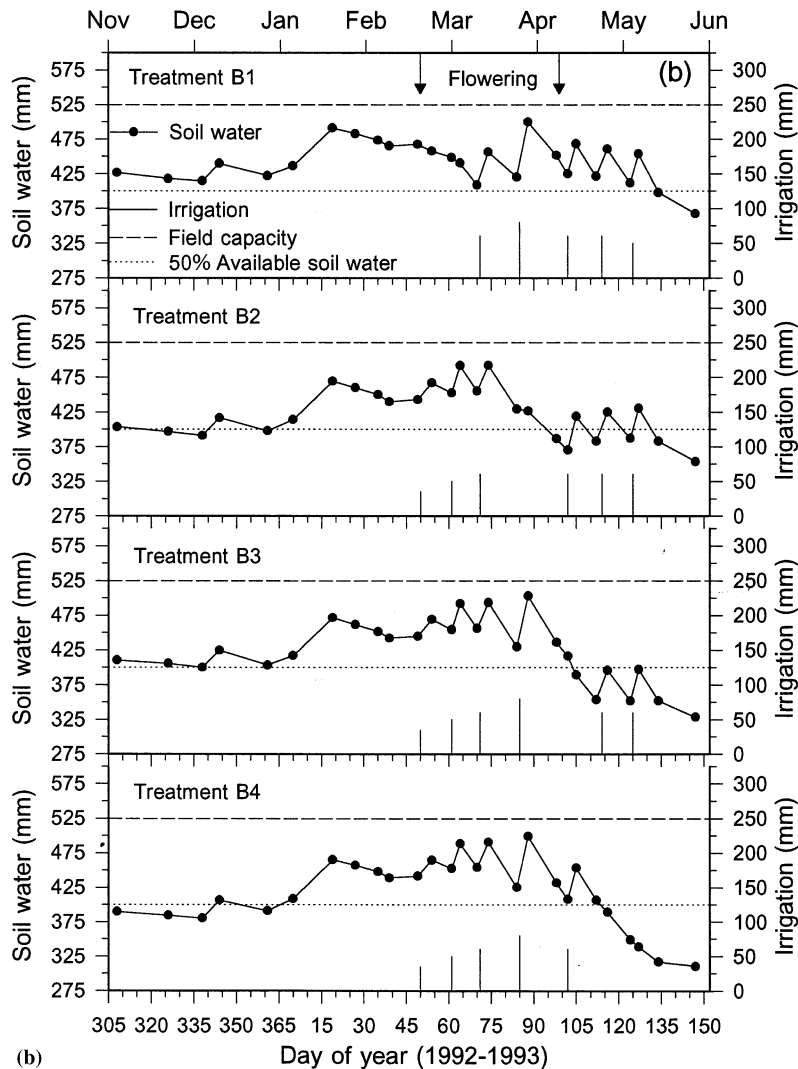


Fig. 2. (Continued)

creased rapidly after the first supplemental irrigation in early December, and the ratios were near 1.0 in early February. All other treatments, except B1, attained ET rates higher than the reference crop evapotranspiration at some point later in the season. The maximum crop coefficient was 1.27 and occurred for treatment BS in late February. The highest ET rate in the season was 9.47 mm/day and occurred for treatment W during the 15–21 April period.

Weekly irrigated treatments, W and WS, attained higher ET rates than the biweekly treatments, B and BS, starting in early April 1993, after the crop was in full bloom. ET for treatment B1, which was not irrigated until 12 March, was lower than all other treatments during early March (mid-flowering), while ET for treatment B2, which was not irrigated from mid-March to early April, was lower than all other treatments during late March to early April (full bloom).

Table 3
Evapotranspiration for irrigation treatments

(a) Calendar dates 1992–1993		Rainfall (mm)	WS		W		BS		B				
Days in period	Irrigation (mm)		ET rate (mm/day)	ET/Eto †	Irrigation (mm)	ET rate (mm/day)	ET/Eto	Irrigation (mm)	ET rate (mm/day)	ET/Eto			
18 Nov 3–Nov 20	18			0.31	0.08		0.43	0.11		0.26	0.07	0.33	0.09
19 Nov 21–Dec 9	19	35	35	0.89	0.36		0.79	0.32		0.76	0.31	0.77	0.31
17 Dec 10–Dec 26	17			1.81	0.87		1.18	0.56	35	1.86	0.89	1.28	0.61
9 Dec 27–Jan 4	9	23		1.29	0.90		0.77	0.54		1.26	0.88	1.64	0.45
14 Jan 5–Jan 18	14	65		1.15	0.86		0.65	0.49		1.24	0.93	0.68	0.51
8 Jan 19–Jan 26	8			2.11	0.76		1.11	0.40		2.41	0.87	1.30	0.47
12 Jan 27–Feb 7	12		35	2.37	0.75		1.78	0.57	35	2.89	0.92	1.85	0.59
10 Feb 8–Feb 17	10	20		2.32	0.98		1.70	0.72		2.46	1.04	1.94	0.82
5 Feb 18–Feb 22	5		20	3.36	1.16	20	1.78	0.62	30	2.84	0.98	2.18	0.75
7 Feb 23–Mar 1	7	8	20	3.89	1.23	20	3.01	0.96		4.01	1.27	2.76	0.88
9 Mar 2–Mar 10	9		35	5.47	1.17	35	5.17	1.11	50	5.66	1.21	5.32	1.14
14 Mar 11–Mar 24	14		80	6.21	1.18	80	6.29	1.19	60	6.31	1.20	6.14	1.16
14 Mar 25–Apr 7	14	20	100	6.97	1.20	100	7.11	1.23	80	6.19	1.07	6.44	1.11
7 Apr 8–Apr 14	7		50	8.21	1.18	50	7.53	1.08	60	5.21	0.75	5.34	0.77
7 Apr 15–Apr 21	7		50	9.36	1.18	50	9.47	1.20		5.93	0.75	6.49	0.82
12 Apr 22–May 3	12		100	7.81	0.91	100	8.19	0.95	60	5.53	0.64	5.96	0.69
10 May 4–May 13	10		50	8.90	0.96	50	8.10	0.87	60	7.09	0.77	7.34	0.79
13 May 14–May 26	13			2.64	0.28		3.15	0.33		2.01	0.21	2.13	0.22
Total rainfall (mm)			171										
Total irrigation (mm)				575	505	710			470	668		620	
Total ET (mm)													
(b) Calendar dates ^b 1992–1993													
		Rainfall (mm)	B1		B2		B3		B4				
Days in period	Irrigation (mm)		ET rate (mm/day)	ET/Eto †	Irrigation (mm)	ET rate (mm/day)	ET/Eto	Irrigation (mm)	ET rate (mm/day)	ET/Eto			
18 Nov 3–Nov 20	18			0.47	0.12		0.38	0.10		0.27	0.07	0.31	0.08
19 Nov 21–Dec 9	19	35		0.68	0.28		0.78	0.32		0.84	0.34	0.93	0.27
17 Dec 10–Dec 26	17			1.05	0.50		1.12	0.54		1.25	0.60	0.93	0.44
9 Dec 27–Jan 4	9	23		0.97	0.68		0.73	0.51		1.02	0.71	0.58	0.41
14 Jan 5–Jan 18	14	65		0.73	0.54		0.71	0.53		0.79	0.59	0.61	0.46
8 Jan 19–Jan 26	8			1.04	0.37		1.19	0.43		1.28	0.46	1.00	0.36
12 Jan 27–Feb 7	12			1.47	0.47		1.66	0.53		1.63	0.52	1.50	0.48
10 Feb 8–Feb 17	10	20		1.79	0.76		1.72	0.73		1.73	0.73	1.73	0.73
5 Feb 18–Feb 22	5			1.90	0.66	35	2.14	0.74	35	2.12	0.73	2.44	0.84
7 Feb 23–Mar 1	7	8		2.47	0.78		3.21	1.02		3.23	1.03	2.87	0.91
9 Mar 2–Mar 10	9			4.41	0.94	50	5.27	1.13	50	5.38	1.15	5.39	1.15
14 Mar 11–Mar 24	14		60	3.47	0.66	60	6.13	1.16	60	6.18	1.17	6.34	1.20
14 Mar 25–Apr 7	14	20	80	4.90	0.84	80	4.49	0.77	80	6.67	1.15	6.68	1.15
7 Apr 8–Apr 14	7		60	6.20	0.89	60	3.91	0.56	60	6.66	0.96	5.49	0.79
7 Apr 15–Apr 21	7			6.70	0.85		5.17	0.65		5.07	0.64	6.66	0.84
12 Apr 22–May 3	12		60	5.80	0.68	60	4.64	0.54	60	5.14	0.60	4.82	0.56
10 May 4–May 13	10		60	7.36	0.79	60	6.47	0.70	60	6.03	0.65	3.19	0.34
13 May 14–May 26	13			2.35	0.25		2.22	0.23		1.80	0.19	0.50	0.05
Total rainfall (mm)			171										
Total irrigation (mm)				320	325	546			345	598		535	
Total ET (mm)													

† ETo is the grass-reference evapotranspiration calculated by the modified Penman equation (Doorenbos and Pruitt, 1977).

^a Evapotranspiration for irrigation treatments WS, W, BS and B in the 1992–1993 study.

^b Evapotranspiration for irrigation treatments B1, B2, B3 and B4 in the 1992–1993 study.

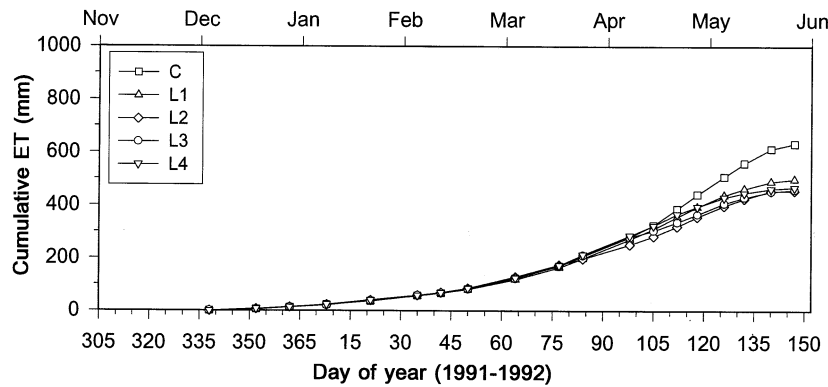


Fig. 3. *Lesquerella* cumulative evapotranspiration with time for all irrigation treatments in 1991–1992.

Withholding irrigation for treatment B3 in mid-April resulted in a slight depression in the ET for that treatment during late April (seed formation). After the last irrigation for treatment B4 on 12 April, its ET declined rapidly, and was the lowest during May (seed ripening).

Fig. 4a,b show the cumulative ET with time for all treatments in 1992–1993. For both the WS and W treatments, ~ 570 mm, or 74 and 80%, of their total ET, and for the B and BS treatments ~ 480 and 470 mm, or 77 and 70%, of their total ET occurred after 1 March (DOY 60), 1993, respectively. For treatments B1, B2, B3 and B4 (Fig. 4b), 77, 75, 76 and 75% of their total ET was after 1 March, respectively.

3.3. Yield

In 1991–1992, final plant population means for treatments ranged from 610000 plants ha^{-1} (for L1) to 747000 plants ha^{-1} (for L4) and treatment differences for plant population were not significant at the 0.05 level according to an analysis of variance (ANOVA). The effect of irrigation on plant dry matter yield was significant at the 0.001 level. Plant dry matter yield (Table 4) for the control treatment was 6280 kg ha^{-1} , and was 26–36% higher than that for the limited irrigation treatments. Dry matter yield was not significantly different between the treatments that received either four irrigations (L1) or received three irrigations at different times (L2, L3 and L4). As indicated before, the total seed yield in 1991–

1992, was severely damaged for all treatments in the heavy rain and hailstorm on 28 May 1992, and the data will not be presented. However, because enough seed was recovered from each treatment to determine seed weight, seed oil content and the lesquerolic acid content of the oil, data for those parameters are presented (Table 4) and discussed, although the results may be misleading due to the questionable effect that the seed shattering had on the sample.

Seed weight was highest for treatment L3 (0.63 g/1000) and lowest for the control and treatment L2 (0.53 g/1000). Lower than normal seed oil contents were obtained for all treatments in 1991–1992, and the irrigation effect was significant at the 0.001 level. The seed oil content for control (21.9%) was significantly higher than that for all other treatments. However, the lesquerolic acid content of the seed oil for L4 (55.4%) was significantly greater than that for all other treatments at the 0.05 level.

In 1991–1992, final plant population means for treatments ranged from 649000 plants ha^{-1} (for B3) to 937000 plants ha^{-1} (for B2), although the treatment differences for plant population were not significant at the 0.05 level according to the ANOVA. Yield data for 1992–1993, are presented for all treatments in Table 5. There were significant irrigation treatment effects for both dry matter yield and seed yield at the 0.05 level. Treatment BS (biweekly irrigation with supplemental early winter irrigation) had the highest dry matter (7020 kg ha^{-1}) followed by treatment B3

Table 4
Yield parameter means for irrigation treatments in 1991–1992

Irrigation treatment	Number of irrigations ^a	Total water applied (mm)	Dry matter yield (kg ha ⁻¹)	Seed weight (g/1000)	Seed oil content (%)	Lesquerolic acid content (%)
Control	7	440	6280a*	0.53b	21.2a	53.2b
L1	4	260	4120b	0.59ab	18.2b	53.6b
L2	3	195	4670b	0.53b	18.6b	53.0b
L3	3	195	4350b	0.63a	16.6b	53.6b
L4	3	195	4050b	0.61ab	17.7b	55.4a

^a Post-emergence irrigations.

^b From post-emergence irrigations.

* Means followed by different letters in a column are significantly different at the 0.05 level.

Table 5
Yield parameter means for irrigation treatments in 1992–1993

Irrigation treatment	Number of irrigations ^a	Total water applied (mm) ^b	Dry matter yield (kg ha ⁻¹)	Seed yield (kg ha ⁻¹)	Seed weight (g/1000)	Seed oil content (%)	Lesquerolic acid content (%)
WS	14	575	6580 abc*	822 ab	0.56 a	24.2 a	51.0 a
W	12	505	6130 bc	821 ab	0.48 a	24.1 a	52.1 a
BS	9	470	7020 a	888 a	0.56 a	23.8 a	52.0 a
B	7	405	6810 abc	797 ab	0.59 a	24.1 a	53.2 a
B1	5	320	6240 abc	780 b	0.57 a	24.6 a	51.1 a
B2	6	325	6880 ab	750 b	0.52 a	23.6 a	51.5 a
B3	6	345	6980 a	807 ab	0.55 a	24.2 a	50.4 a
B4	5	285	6040 bc	742 b	0.48 a	24.0 a	52.4 a

^a Post-emergence irrigations.

^b From post-emergence irrigations.

* Means followed by different letters in a column are significantly different at the 0.05 level.

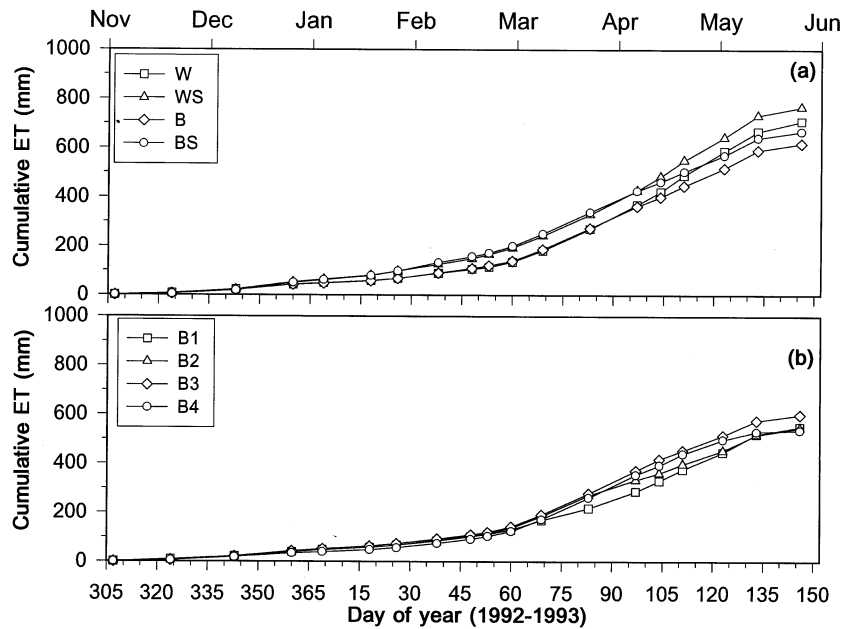


Fig. 4. *Lesquerella* cumulative evapotranspiration (ET) with time for irrigation treatments W, WS, B and BS (a), and treatments B1, B2, B3, B4 (b) in 1992–1993.

(6980 kg ha⁻¹), a biweekly irrigation treatment with one irrigation withheld during mid-April (after full bloom). The lowest dry matter yield (6040 kg ha⁻¹) was for treatment B4 (no irrigation after 12 April). The dry matter yield for both the BS and B3 treatments was significantly greater than that for the W and B4 treatments.

Treatment BS also had the highest seed yield (888 kg ha⁻¹). Seed yield for BS was 14, 18 and 20% higher than that for treatments B1, B2 and B4, respectively, and the differences were significant at the 0.05 level. The total ET (Table 3a) for the BS (668 mm) were 21, 22 and 25% higher than that for the B1, B2 and B4 treatments, respectively. The W and WS treatments had the next highest seed yields after the BS, but the yields were not significantly different than those for any other treatment. Treatment means for seed weight varied from 0.48 to 0.59 g/1000, from 23.6 to 24.6% for seed oil content, and from 50.4 to 53.2% for the lesquerolic acid content in 1992–1993. However, the effect of irrigation on those

yield parameters was not significant at the 0.10 level according to ANOVA.

3.4. Yield-evapotranspiration relations

The relationship between dry matter yield and total ET is shown in Fig. 5 for 1991–1992. A first-order linear regression equation fit to the data had a high coefficient of determination (R^2) of 0.76 and indicates that the dry matter increased linearly with ET over the range of treatments for that year. In contrast, the relationship between dry matter yield and total ET for 1992–1993 (Fig. 6a), was better described by a second-order polynomial than a first-order equation, although the resultant regression R^2 of 0.30 was not high. The maximum dry matter yield for 1992–1993, based on the polynomial equation in Fig. 6a, was achieved at a total ET of 653 mm. The relationship between seed yield and ET for 1992–1993 (Fig. 6b), was also described by a second-order polynomial with an $R^2 = 0.47$. Based on the equa-

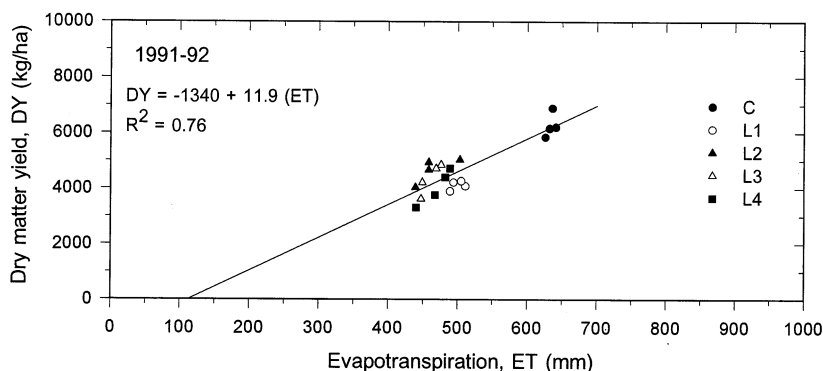


Fig. 5. Relationship between *Lesquerella* dry matter yield (DY) and total evapotranspiration (ET) in 1991–1992.

tion in Fig. 6b, the maximum seed yield corresponded to 674 mm of total ET.

4. Discussion

The ET for *Lesquerella* varied from 460–634 mm in 1991–1992, and from 535–767 mm in 1992–1993. Earlier *Lesquerella* studies indicated that 600–625 mm of water is required in central Arizona for top seed yields. For 1991–1992, a total ET of 634 mm for the control treatment was similar to the water requirement estimated from the previous work. For 1992–1993, the maximum dry matter and seed yield were obtained for the BS treatment at 668 mm of total ET, and yield-ET regression curves (Fig. 6a,b), indicated the maximum dry matter and seed yield occurred at 653 and 674 mm of ET, respectively. Thus, results for 1992–1993, suggest that the crop water requirement for *Lesquerella* may be somewhat higher than 625 mm, although it was possible that drainage water from the bottom of the measured 2.1 m soil layer occurred for some treatments in 1992–1993, and may have been included in the soil water balance ET. Presumably, this was the case for both weekly irrigation treatments (WS and W) because the higher ET values (< 700 mm) for those treatments did not translate to higher yields.

The results showed that the majority of the total water use for *Lesquerella* occurred after initial flowering (\approx late February), and that the

daily crop ET was as high or higher than reference crop evapotranspiration starting shortly after the onset of flowering. In both experiments, crop ET rates for *Lesquerella* reached 9 mm/day or more for well-watered treatments and generally peaked during seed formation in late April. As suggested by the data from these experiments, a water management that allows $\sim 50\%$ depletion of the available soil water, from late February through mid-May, can result in maximum plant production and seed yield. This soil water regime can be maintained with irrigation every 2 weeks for soils with water holding characteristics similar to this study. After *Lesquerella* begins flowering, reduced water availability may have an adverse effect on seed yield. For example, in 1992–1993, seed yield for treatment B1, which was not irrigated until 12 March (mid-flower), and treatment B2, which received no irrigation from 13 March to 11 April (mid-flower to full bloom), were significantly lower than that for BS, the treatment with the highest seed yield in the study. However, with a properly timed water deficit, it may be possible to achieve high *Lesquerella* seed yields with less water applied. This was indicated by treatment B3, which was not irrigated from 27 March to 23 April (full bloom to seed formation), and was not significantly lower in yield than treatment BS. This suggests that after the crop was at full bloom, limited water availability had no effect on the seed yield. Although it was apparent that if irrigation is not returned to the crop during the formation and ripening of the

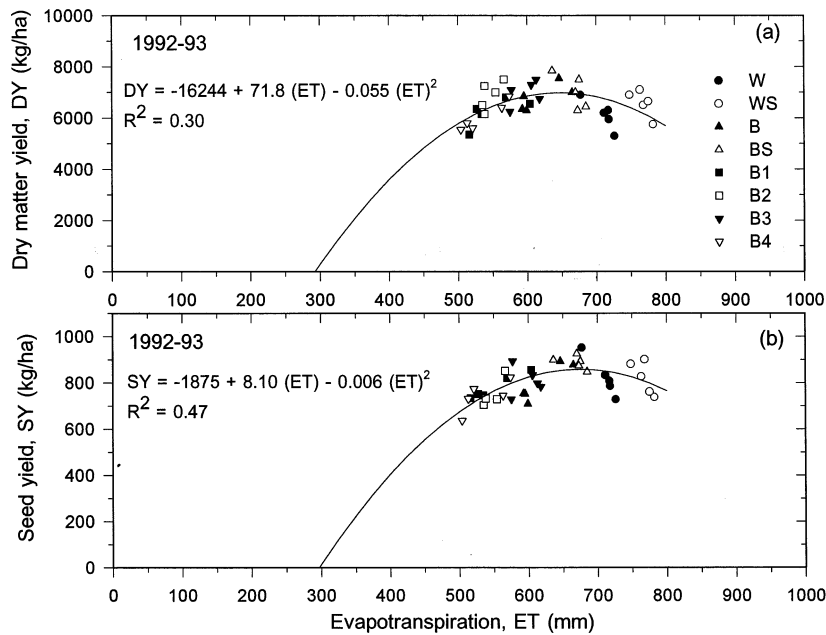


Fig. 6. Relationship between *Lesquerella* dry matter yield (DY) and total evapotranspiration (a), and seed yield (SY) and total evapotranspiration (b) in 1992–1993.

seed, as was the case for treatment B4, which received no irrigation after 12 April, the seed yield will be diminished. It was less clear, however, whether the significantly lower dry matter yield for the limited water treatments in 1991–1992, resulted entirely from the earlier termination of irrigation (on 23 April for treatments L1, L2 and L3 treatments and on 12 April for L4) or was partially influenced by irrigation regime earlier in the season. Since plant biomass was not measured until June, we cannot establish this relation. However, because dry matter yield was similar for all limited water treatments, the earlier termination of irrigation relative to the control was likely the dominating influence.

Seed oil content and other seed parameters reported for the 1991–1992 study are probably of little value. When shatter occurred in late May 1992 the older, fully mature capsules were the ones that were lost. Consequently, the capsules that remained were more likely to have seed that was not fully ripened, resulting in low seed oil contents.

The use of early winter supplemental irrigation in 1992–1993, may have had a marginal effect on the yield production for the biweekly treatment (BS), which attained higher yield and oil components than all other treatments. Higher rates of ET that were indicated for the two supplemental treatments (BS and WS) in early winter may have resulted in earlier vegetative development. However, the application of early supplemental irrigations for the WS treatment did not have an apparent yield benefit for that treatment. Since the seed yield for the WS treatment was lower than the BS yield, other factors that occurred later in the season, e.g. nutrient leaching from more frequent irrigations, may have lowered the yield for the WS treatment from its potential. There was also plentiful rainfall in the winter of 1992–1993, which may have masked the true benefit of early winter irrigation. In years having less frequent precipitation during winter, the use of early irrigation may be more important to yield.

5. Conclusions

Over two seasons in central Arizona, the total water requirement (evapotranspiration) of *Lesquerella* for maximum yield production was 634 mm for treatment C in 1991–1992, and 668 mm for treatment BS in 1992–1993. However, a major portion of the water requirement, 70–80%, for the fall-planted (October) *Lesquerella* was used after the onset of flowering (late February). Under well-watered treatments, *Lesquerella* crop ET during flowering to seed formation was as high or higher than that for a meteorologically-based reference crop evapotranspiration. The results from the 2 year study suggest that *Lesquerella* should not be water-stressed during flowering (late February through late March), although it appears that it can tolerate reduction in water availability after the crop has reached full bloom (mid-April). However, it was evident that adequate water is needed during the formation and ripening of the seed (late April), to avoid reduction in the seed yield. Providing supplemental irrigation in early December and February increased the evapotranspiration rate during winter, but did not have an affect on the seed yield for a weekly irrigation treatment. However, the supplemental winter irrigation for a biweekly irrigation treatment may have had a positive effect on the yield production for that treatment, which achieved the highest dry matter and seed yield in 1992–1993. A recommended irrigation management is to allow crop water extraction from the soil until the available soil water is depleted to ~ 50%. This soil water regime can be accomplished with about seven irrigations given at 2 week intervals starting in late February. For soils with a medium water holding capacity similar to this study, a shorter irrigation cycle (e.g. every 7 days) is not necessary for high yields and may have a negative impact on yield. Less frequent surface irrigation would be preferable for most commercial farm operations in the desert Southwest.

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